

Velocity Dispersion of Dissolving OB Associations Affected by External Pressure of Formation Environment

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ABSTRACT

This paper presents a possible way to understand dissolution of OB associations (or groups). Assuming rapid escape of parental cloud gas from associations, we show that the shadow of the formation environment for associations can be partially imprinted on the velocity dispersion at their dissolution. This conclusion is not surprising as long as associations are formed in a multiphase interstellar medium, because the external pressure should suppress expansion caused by the internal motion of the parental clouds. Our model predicts a few km s^{-1} as the internal velocity dispersion. Observationally, the internal velocity dispersion is $\sim 1 \text{ km s}^{-1}$ which is smaller than our prediction. This suggests that the dissipation of internal energy happens before the formation of OB associations.

Subject headings: open clusters and associations: general — ISM: clouds — stars: formation — turbulence

1. Introduction

Open clusters and OB associations (or groups) have been investigated from various points of view, considering spectral types of member stars (e.g., Sanford 1949; Svolopoulos 1961; Levato & Malaroda 1975; Abt & Levato 1975; Trumpler 1988; Morrell, Garcia, Levato 1988; Sears & Sowell 1997; Wang & Hu 2000; Piatti et al. 2002), mass function (e.g. Jaschek & Jaschek 1957; Frolov 1975; Lee & Kim 1983; Ann & Lee 1989; Phelps & Janes 1993; de La Fuente Marcos 1995; von Hippel et al. 1996; Sagar & Griffinths 1998; Barro y Navascues et al. 2001; Prisinzano et al. 2003), abundance (e.g. Demarque & Heasley 1971; Chaffee, Carbon, Strom 1971; Zappala 1972; McClure 1972; Barry & Cromwell 1974; Norris & Hawarden 1978; Claria 1979; Panagia & Tosi 1980; Cameron 1985a, 1985b; Smith & Suntzef 1987; Gilroy 1989; Boesgaard 1991; Gratton & Contarini 1994; Edvardsson et al. 1995; Tiede, Martini, Frogel 1997; Sarajedini 1999; Gonzalez & Wallerstein 2000; Randich et al. 2001; Mathys et al. 2002; Friel et al. 2002), kinematics (e.g. Gieseking 1981; Hron 1987; Lynga & Palous; Friel 1988; Sagar &

Bhatt 1989; Scott, Friel, & Janes 1995; Samner et al. 2000; Gonzalez & Lapasset 2000), and so on.

The origin and evolution of clusters are also a classical set of problems (e.g. Starikova 1966; Kaliberda 1973; Palous et al., 1977; Burki 1978; van den Bergh 1981; Turner 1985; Danilov 1987; Battinelli & Capuzzo-Dolcetta 1991; Phelps & Janes 1994; van den Ancker et al. 1997; Elmegreen & Efremov 1997; Belikov et al. 2000; Garcia & Mermilliod 2001). Recently, understanding these problems has been recognized to be very important if we want to know how disks of spiral galaxies formed and evolved (e.g., Efremov & Elmegreen 1998a, b; Nomura & Kamaya 2001), because star complexes and associations are fundamental and elementary cells of star formation (e.g. Efremov 1995).

This paper tries to investigate some elemental connections between the formation and evolution of clusters. In particular, the dissolution process of OB associations (or groups) is studied.

2. Analysis

First of all, we define a *parental cloud* in which OB association is formed. The parental cloud is made of the typical cold component of interstellar medium (ISM) of the Milky Way. We focus on the origin and evolution of OB associations at the present epoch.

2.1. Assumptions

We set up our problem with the following four assumptions: (1) At the formation epoch, parental clouds are in virial equilibrium, affected by the external pressure of the ISM. This initial condition is necessary since the various phases of ISM are roughly in pressure equilibrium (Myers 1978). Pressure jumps at surfaces of parent clouds are unexpected or of little significance. (2) Gas of parent clouds is removed rapidly. This means there is a sufficient chance for parental clouds or cloudlets to be in pressure equilibrium before star formation starts inside them. In other words, the initial temperature and density of gas content of parental clouds are 100 K and 100 cm^{-3} , respectively, with an external pressure of $\sim 10^{-12} \text{ ergs cm}^{-3}$. This becomes possible if size of parental clouds is initially small. After growing via coagulation of blobs of cold phase ISM and/or accumulation of warm phase ISM due to radiative cooling, dynamical collapse occurs when size of parental clouds becomes larger than the Jeans-length. Soon after the formation of clusters, the parental gas is removed very rapidly by the activity of massive stars. Thus, as long as some massive stars are formed in the multi-phase ISM, rapid removal assumption for the parental clouds can be very reasonable. (3) To show the importance of the external pressure, we drop the effect of angular momentum and the figure rotation of the parental cloud. (4) To find the final velocity dispersion, we adopt energy conservation law for the stellar component.

2.2. Virial equilibrium

The virial equilibrium for a parental cloud is expressed as

$$2K_0 + W_0 = 3p_0V_0, \quad (1)$$

where V is volume of the parental cloud, K is kinetic energy, p is external pressure, W is gravitational energy, and the subscript 0 denotes the

initial condition (e.g. Hill 1980). Denoting velocity dispersion as $\langle v_0^2 \rangle$, we estimate

$$\langle v_0^2 \rangle = \frac{GM_0}{2R_0} + \frac{3p_0V_0}{M_0}. \quad (2)$$

Here, G is the gravitational constant, M is mass of a parental cloud, R is characteristic size of a parental cloud, and the subscript 0 again denotes the initial condition.

When stars are formed in a parental cloud, the total energy of stellar component is estimated as

$$E_{\text{star}} = K_{\text{star}} + W_{\text{star}} = \frac{M_{\text{star}} \langle v_0^2 \rangle}{2} - \frac{GM_{\text{star}}^2}{2R_0} \quad (3)$$

where E_{star} is total energy, K_{star} is kinetic energy, W_{star} is gravitational energy, and M_{star} is total mass of stellar component. Here, rapid removal assumption is adopted.

2.3. Energy conservation

As well-known, OB associations are gravitationally unbound system. Thus, the sign of the total energy is always positive. We let $\langle v_1^2 \rangle$ be the current velocity dispersion, and estimate the energy for the dissolving association as

$$E_1 = \frac{M_{\text{star}} \langle v_1^2 \rangle}{2} \quad (4)$$

where E_1 is total energy of the association. At this epoch, the gravitational energy of the association has become negligible.

With energy conservation,

$$E_1 = E_{\text{star}}, \quad (5)$$

we find

$$\langle v_1^2 \rangle = \frac{GM_{\text{star}}}{2R_0} \left(\frac{M_0}{M_{\text{star}}} - 2 \right) + \frac{3p_0V_0}{M_0}. \quad (6)$$

It should be noted that we are considering gravitationally unbound system. That is, the star formation efficiency in mass, $\Gamma_{\text{SFE}} \equiv M_{\text{star}}/M_0$, is smaller than ~ 0.5 (i.e. $M_0/M_{\text{star}} > 2.0$).

2.4. Estimate of velocity dispersion

The two terms of the right hand side of Eq.(6) are denoted as

$$A_1 = \frac{GM_0}{2R_0} (1 - 2\Gamma_{\text{SFE}}) \quad (7)$$

and

$$B_1 = \frac{3p_0 V_0}{M_0}, \quad (8)$$

respectively.

For A_1 , it is reasonable for us to estimate $R_0 \sim R_J$, where R_J is half of the Jeans wavelength:

$$R_J = \frac{a_0}{2} \left(\frac{\pi}{G\rho_0} \right)^{0.5} \quad (9)$$

where a_0 is the sound speed and ρ_0 is mean density at the formation epoch. With hypothesis of spherical geometry for a parental cloud, we find

$$A_1 = \frac{\pi^2}{6} (1 - 2\Gamma_{\text{SFE}}) \times a_0^2. \quad (10)$$

The other term B_1 is also expressed in terms of a_0 ;

$$B_1 = 3a_0^2 \quad (11)$$

with the assumption of spherical geometry for a parental cloud. Hence, we find that both A_1 and B_1 are on the order of a_0^2 . In the current case, a_0 is about 1 km s⁻¹. Hence, $\sqrt{\langle v_1^2 \rangle}$ is on the order of 1 km s⁻¹ as

$$\sqrt{\langle v_1^2 \rangle} = \left[\frac{\pi^2}{6} (1 - 2\Gamma_{\text{SFE}}) + 3 \right]^{0.5} a_0. \quad (12)$$

Note that B_1 (i.e. contribution from the external pressure) can dominate A_1 , if $\Gamma_{\text{SFE}} \sim 0.1$ and/or the geometry of parental clouds is not far from round shape.

3. Discussion

3.1. Aspect ratio of cloud configuration

In general, geometrical configuration of interstellar clouds is not spherical. It seems to be filament. If angular momentum and figure rotation of the clouds are neglected, the virial equilibrium for a filamentary cloud is expressed roughly as

$$2K_0 + W_0 = 4\pi R_0^2 Z_0 p_0, \quad (13)$$

where R_0 is the size of semiminor axes and Z_0 is that of semimajor axes. From this equation, we find that as long as the aspect ratio, R_0/Z_0 , of the cloud configuration is not much smaller than unity,

our spherical assumption is not so crude. Indeed, the aspect ratio of the parental clouds is not so small, since the self-gravity of the parental cloud is comparable to the internal pressure at the formation epoch. We remember $R_0 = R_{\text{Jeans}}$ which means that the internal thermal energy is comparable to the self-gravitational energy. Then, we confirm qualitatively that B_1 can dominate or be comparable to A_1 for determining the final velocity dispersion of associations.

For general purpose, the scalar virial theorem is not adopted. The tensor virial theorem (Weber 1976) is necessary, especially when the angular momentum and figure rotation are important. If the effects of angular momentum and figure rotation are comparable to that of the external pressure, the coupling among the three effects (external pressure, angular momentum, and figure rotation) may be reflected in the internal velocity dispersion of OB associations. In future work, we try to examine the angular momentum and figure rotation rigorously.

If the overall stellar distribution of associations is far from spherical, our consideration may become meaningless. In Efremov (1995), spatial distribution of Cepheids and membership of OB association are examined. According to his paper, fortunately, the configuration of OB associations is not so far from spherical (see also Parker et al. 2001). Furthermore, stellar density distribution of η Cha cluster member seems to be spherical (Mamajek, Lawson, & Feigelson 2000).

3.2. Gravitational effect of disk

In the final process of dissolution of OB associations, the external gravity of the Milky Way can be effective. However, for young and/or intermediate age OB associations, the external gravity field is not so critical (e.g. Brown, Dekker, & de Zeeuw 1997). This is because, the initial size of associations can be less than ~ 10 pc (Brown et al. 1997), while the length scale for the tidal force from the galactic disk can be about 10 pc (e.g. Keenan, Innanen, & House 1973). Thus, velocity dispersion of young associations can retain the information of parental clouds affected by the external pressure.

3.3. Comparison to observation

OB associations expand because of their unbound nature. The expansion can be detected if and only if the correct mean streaming motion of the association with respect to the Sun is subtracted from the observed proper motion and radial velocities (e.g. Steffey 1973). Even if we use the data of *Hipparcos*, this is a very difficult task (de Zeeuw et al. 1999). Fortunately, de Bruijne (1999) has succeeded in finding the internal velocity dispersion of nearby OB associations with the assumptions of isotropy and compactness. According to this work, the internal velocity dispersion of $\sqrt{\langle v_{\text{obs}}^2 \rangle}$ is about $1.0 - 1.5 \text{ km s}^{-1}$. Our theoretical model predicts $\sqrt{\langle v_1^2 \rangle} \simeq 2 \text{ km s}^{-1}$ if $\Gamma_{\text{SFE}} = 0.1$. The author thinks this estimate is consistent with observational constraint.

However, our estimate of $\langle v_1^2 \rangle \simeq 4 \text{ km}^2 \text{ s}^{-2}$ is slightly larger than $\langle v_{\text{obs}}^2 \rangle \sim 1 \text{ km}^2 \text{ s}^{-2}$, which suggests two points. (1) The sound speed of the parental clouds is reduced by the formation of hydrogen molecules, which increases the mean molecular weight. This effect decreases $\langle v_1^2 \rangle$ by a factor of 0.5, that is $\langle v_1^2 \rangle \rightarrow 2 \text{ km}^2 \text{ s}^{-2}$. The difference between $\langle v_1^2 \rangle$ and $\langle v_{\text{obs}}^2 \rangle$ becomes small, so further dissipation of internal energy of the parental clouds may be needed to reduce $\langle v_1^2 \rangle$. (2) Dissipation of energy during the formation of OB associations can be important. This decreases the internal velocity dispersion before the rapid gas removal. If so, the observational internal velocity of $\sqrt{\langle v_{\text{obs}}^2 \rangle}$ should be always smaller than our $\sqrt{\langle v_1^2 \rangle}$. Our theory for $\sqrt{\langle v_1^2 \rangle}$ presents the upper-bound for internal velocity dispersion of young OB associations.

We would like to comment on some detailed studies of the velocity dispersion of open clusters. McNamara & Sekiguchi (1986) reported $\sim 1.0 \text{ km s}^{-1}$ for M 35. Girard et al. (1989) insist velocity dispersion of M67 is $\sim 0.8 \text{ km s}^{-1}$ (see also McNamara & Sanders 1978).

3.4. Comments on interstellar turbulence

Throughout this paper, we have mentioned on the effect of the interstellar turbulence. Here, some comments are presented. To determine a_0 , it is natural for us to regard a_0^2 as the sum of two components, thermal and turbulent motion, which suggests that the kinematics of young associations

reflects the turbulent motion of the parental clouds (Elmegreen, Kimura, & Tosa 1995). This last possibility may explain one of the elemental processes of the relation between age and distance among clusters and associations (Efremov & Elmegreen 1998a, 1998b).

3.5. Comments on numerical work

The dissolution process is examined precisely by Brown, Dekker, & de Zeeuw (1997). The internal velocity dispersion of their initial conditions is a few km s^{-1} . Our model favors a similar internal velocity. According to their results, the discrepancy between the kinematic and nuclear ages of OB associations is attributed to underestimates of the kinematic age. This may be occurred because of overestimation of the internal velocity dispersion, as in our model. In the author's opinion, the dissipation of thermal and kinetic energy of the parental clouds before the formation of OB associations is important in decreasing the internal (i.e. expanding) velocity of associations.

The importance of the external pressure is also suggested numerically by Elmegreen, Kimura & Tosa (1995). According to their numerical work, the internal velocity dispersion of forming OB association is determined by the shock condition. Obviously, the thermal condition of the parental clouds is determined by the external pressure via flux-conservation laws of mass, momentum, and energy. The difference between their work and ours is very clear. That is, we insist that even if the associations are isolated at their formation epoch (i.e. not sequential formation mode), the external pressure can affect their internal kinematics. The isolated formation mode of OB associations is important when the turbulent speed of the ISM is larger than the expansion speed of the HII region (Nomura & Kamaya 2001). Of course, further theoretical consideration is necessary.

4. Summary

We show that the internal velocity dispersion at the dissolution epoch of OB associations is affected by the external pressure on their parental clouds. The observations show the velocity dispersion of dissolving association to be $\sim 1 \text{ km s}^{-1}$, which is smaller than our estimate of a few km s^{-1} . The conclusion is that motion of forming stars in OB

associations may have been decreased by energy dissipation inside the parental cloud.

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